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TUNABLE SYNCHRONOUSLY PUMPED INTRA-CAVITY TWO-STAGE OPTICAL FREQUENCY UPCONVERSION

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Optical parametric oscillation (OPO) with intracavity sum-frequency generation (SFG) of the signal and pump has been studied theoretically and numerically, using the CW plane-wave theory as well as a numerical code developed to simulate either synchronously pumped pulse propagation or walk-off effects in one transverse dimension. The configuration where the SFG crystal precedes the OPO crystal in the cavity gives stable high-efficiency conversion over a larger range of pump intensity, as well as lower power loading on the OPO crystal. About 85 percent conversion efficiency from 1.064 μm to 589 nm is predicted at pump intensities up to 9 MW/cm^2 for a device using $AgGaS_2$ and KTP crystals. Also, the angular distribution of parametric fluorescence from $AgGaS_2$ has been calculated in good agreement with measurements made at the Phillips Laboratory.

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The research reported here consists of theoretical and numerical studies of an optical parametric oscillator (OPO) in which the optical cavity contains a second crystal (in addition to the OPO crystal) for sum-frequency generation (SFG) of the pump and OPO signal frequencies. Related experimental work is being carried out by Drs. K. Koch and S. Chakmakjian of the Phillips Laboratory (PL/LITN) and E. Cheung of UCLA (visiting researcher at the PL/LITN). Papers reporting this work have been completed or are in preparation and are listed at the end of this report. These papers provide full details of the work carried out under this contract.

The motivation for this work is to develop an efficient one-laser source of 589 nm sodium D-line radiation. This radiation would be used for guide-star generation in the mesospheric sodium layer for compensated atmospheric imaging. However, the technique studied is applicable to the generation of a continuous range of frequencies between the pump frequency ω_p and $2\omega_p$ and so should have many other applications. For the guide-star application we consider a CW mode-locked Nd:YAG pump laser operating at wavelength $\lambda_p = 1.064$ μm. A $AgGaS_2$ OPO crystal converts this radiation to a signal at $\lambda_s = 1.319$ μm and an idler at $\lambda_i = 5.504$ μm. The signal and pump frequencies are then summed in a KTP crystal to give the desired $\lambda_d = 589$ nm light. The OPO cavity resonates only the signal frequency.

We have carried out a theoretical study [1] based on the CW plane-wave equations for the OPO and SFG interactions. This study shows that a stable high-efficiency operation is to be expected over a wide range (factor of 12) in the pump intensity. Moreover, the SFG $\rightarrow$ OPO configuration, where the pump radiation is first incident on the SFG crystal, is superior to the opposite crystal ordering (the OPO $\rightarrow$ SFG configuration). Besides giving a stable, high-efficiency operation over a wider range of pump intensity, the SFG → OPO configuration gives lower power loading on the OPO crystal. This loading can actually be less at saturation than the incident pump intensity. The power conversion efficiency to 589 nm is about 85 %.

In a second paper [2] we consider the effects of phase mismatch in the SFG crystal in the SFG → OPO configuration produced by detuning the angular orientation of this crystal slightly. This analysis is also based on the CW plane-wave theory. We find that the dynamic range for stable high-efficiency operation (quantum efficiency greater than 40 %) increases to a factor of 34 variation in the pump intensity. In fact, stable operation occurs over the whole range of pump intensity.

The CW plane-wave analysis, though very encouraging, does not provide a complete description of the physics for a device which is synchronously pumped by a train of mode-locked pulses. A complete description would need to account for both temporal effects and transverse effects in two dimensions. Such a complete description appears to be impractical. However, we have developed a code which accounts for either temporal effects or transverse effects in one dimension (most usefully, the dimension in which walk-off effects occur). Since the temporal and transverse effects enter the theory in a similar fashion, the same code with different input parameters can be used to study either temporal or transverse effects [3]. The code treats temporal effects, for example, by means of a multipass pulse propagation simulation. The partial differential equations are integrated by a method which combines the beam-propagation method (using the fast Fourier transform) with the 4th-order Runge-Kutta method. Simulations are possible of the OPO alone, the SFG → OPO or OPO → SFG configurations, or an OPO in which intracavity second-harmonic generation (SHG) of the signal at ω_s is carried out in lieu of SFG. The results for the SFG → OPO configuration confirm the stable high-efficiency operation found in Paper [1]. Both temporal pulse shapes and spectra are calculated and converge to steady state if the pump intensity is not too high. However, in contrast to Paper [2], steady-state high-efficiency behavior has not been obtained at a higher pump intensity because of multifrequency instabilities. Although these instabilities can be largely suppressed by spectral filtering of the signal, this results in undesirable reduction of the gain. Thus, it appears best to work at pump intensities below the instability threshold. This is not a serious limitation since excellent conversion efficiency and stable operation are obtained up to a 9 MW/cm^2 pump intensity for a 2 cm length of $AgGaS_2$ crystal, whereas the damage threshold of this material is 20 MW/cm^2.

$AgGaS_2$ is a relatively little-used nonlinear crystal but is favored for our application because it transmits the long-wavelength idler radiation. In order to better characterize this material, our experimentalists have measured the parametric fluorescence from this material when it is irradiated by 1.064 μm radiation [4]. G. Moore has developed a theory based on Fermi's Golden Rule which is in excellent agreement with the measured results. It is found that the signal photons are emitted in cones with shorter wavelengths at larger cone angles. The cone axis is not in the pump direction but is in the direction for which the signal and idler Poynting vectors are collinear. When the pump beam radius is sufficiently small, the fluorescence is not uniform around the cone. Instead there is a "hot spot" in the signal brightness. Signal photons in this hot spot are correlated with idler photons whose Poynting vector is collinear with the pump Poynting vector. Similarly an idler hot spot is expected whose photons are correlated with signal photons having Poynting vectors collinear with the pump Poynting vector. Our detector is not sensitive at the long wavelength of the idler radiation from $AgGaS_2$, but an analogous experiment using KTP pumped at 532 nm appears feasible and is in progress.

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